

CALIFORNIA STORMS AS VIEWED BY SACRAMENTO RADAR

ROBERT L. WEAVER

Office of Hydrology, Weather Bureau, ESSA, Washington, D.C.

ABSTRACT

The WSR-57 radar at Sacramento provides an opportunity to observe mountain effects on precipitation and on radar echo patterns. Radar patterns representing a wide range of weather situations are described and interpreted in light of concurrent gage precipitation measurements.

Comparisons are made between gage precipitation depth and that indicated by the radar. The frequent underestimation by radar of rainfall on windward slopes is attributed to the small drop size and low formation level of the orographic precipitation. Overestimation on lee slopes is in part due to evaporation before the precipitation reaches the ground.

1. INTRODUCTION

The Sacramento, Calif. WSR-57 radar located in the Central Valley at a low elevation (fig. 1) is situated uniquely to observe effects of mountainous terrain on storms moving inland from the Pacific Ocean. Until a recent move to a higher rooftop location, an upward antenna tilt was required to minimize terrain clutter from the Sierra foothills and coastal mountains. This tilt limited range and aggravated the effects of overshooting except at short ranges. Precipitation was detected to about 120 mi., or over most of the northern two-thirds of California. The problem of overshooting is more serious with respect to orographic precipitation (that part induced by laminar upslope flow) than to the higher-level precipitation from purely convergence causes. At the same time, the radar usually overestimates precipitation in the lee of the Coast Range. At Sacramento these mountain effects are added to those that contribute to variation of radar visibility (the ability of radar to detect precipitation) in flat terrain.

PURPOSE AND ORGANIZATION

The purpose of this paper is to provide experience to forecasters and hydrologists in relating radar patterns to precipitation patterns and surface weather maps in a variety of weather situations. To accomplish this purpose the paper discusses gage precipitation vs. radar-estimated precipitation, weather patterns as seen by radar, and estimates of precipitation components. These subjects are of particular interest to the hydrologist, the synoptic analyst and forecaster, and the hydrometeorologist.

DATA

Data chosen for analysis are primarily from the major storms of October 10-13, 1962 and January 30-February 1, 1963, along with special features of several minor storms. The surface weather maps in the figures were

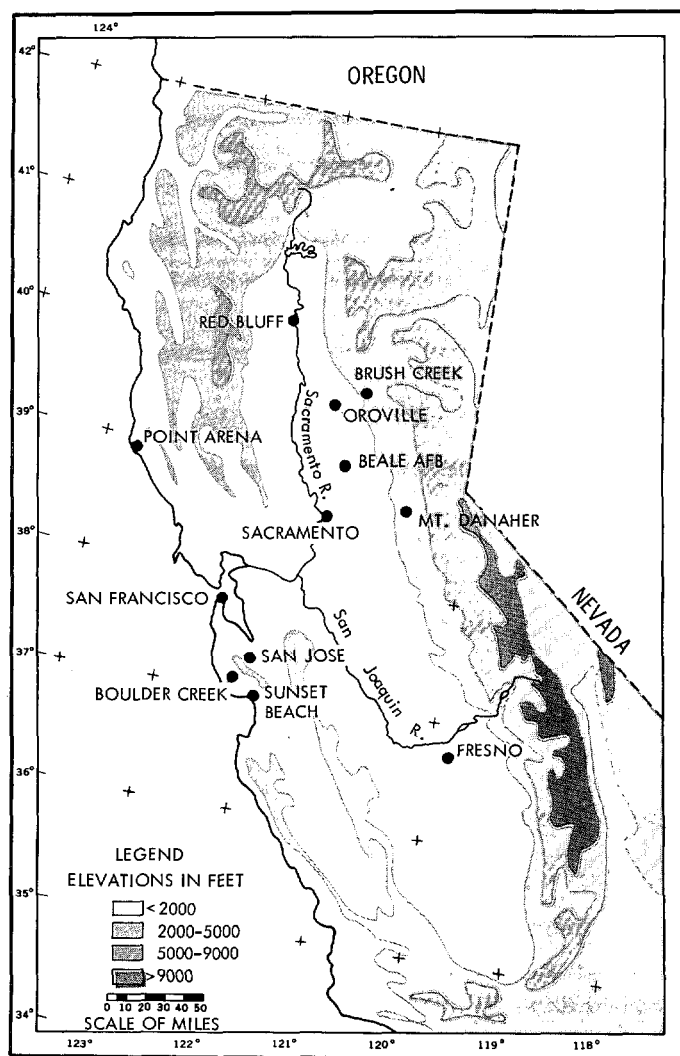


FIGURE 1.—Generalized terrain map of northern and central California.

copied from maps of the Weather Bureau National Meteorological Center. The radar echo charts shown were transcribed from the PPI-scope by the radar meteorologist each hour. The echoes are depicted in four intensity ranges which, based on the accepted radar-intensity rainfall relation [1], represent on the average instantaneous precipitation intensities equivalent to less than 0.2 in. (weak), 0.2 in. to 1 in. (moderate), 1 in. to 5 in. (strong), and more than 5 in. per hr. (very strong). Also used in this study are station radar precipitation intensities read from the A-scope twice each hour.

An essential step in this study was to superimpose hourly isohyets (drawn to gage data) on the hourly radar echo charts for each storm. The hourly radar echo charts and hourly isohyetal patterns often complement each other in providing details of motion and structural changes of meso- and synoptic-scale weather systems, particularly fronts. Hourly isohyetal analysis in areas of sparse data is often improved by reference to the radar displays at beginning and ending of the hour; likewise, interpretations of radar sequences are often clarified by the hourly precipitation patterns.

2. RAIN GAGE-RADAR COMPARISONS

How well does the Sacramento radar replicate the precipitation pattern? At WSR-57 locations in flat terrain this depends largely on range, with decreasing accuracy as range increases [2]. Radar return depends also on size of water or ice particles filling the beam [3]. Regional variations are observed in the response of radar return to precipitation [4]. A comparison of hourly and of daily totals of Sacramento radar-estimated precipitation with observed precipitation shows wide variation among both gaging stations and storms. It appears that part of this variability depends on the method by which the precipitation forms and on the environment through which it falls:

(1) On the windward slopes, that part of the precipitation formed by mechanical lifting of a laminar flow beyond saturation involves small drops and the process of formation favors lower levels [5]. However, the characteristic drop size of convergence precipitation (that formed independent of terrain) is larger and the predominant level of concentration is higher than that of the orographic rain. These factors favor weaker radar signal return when orographic precipitation predominates, especially at ranges where, with the antenna at a 1° tilt to avoid terrain clutter, the beam overshoots drops in lower levels.

(2) The ratio of rain reaching the ground (gage catch) to rain "seen" by the radar (drop size and density sampled as indicated by the return signal strength) is lowest over lee areas where evaporation in lower levels is most effective in reducing precipitation. Low ratios may occur for the same reason over Central Valley areas on the southern edge of a storm where precipitation falls through a channeled southerly flow of dry air in lower levels.

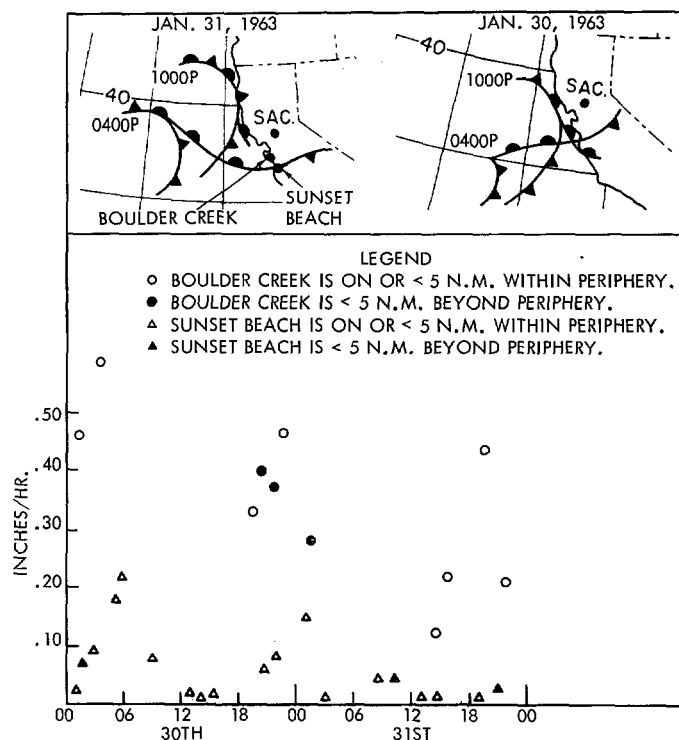


FIGURE 2.—January 30-31, 1963 threshold intensities at Boulder Creek (○) 95 n. mi., and Sunset Beach (△) 103 n. mi. from the Sacramento radar.

There are various methods of comparing precipitation intensity with that indicated by radar. Station hourly gage readings are compared below with station radar rates (1) estimated from the hourly radar charts and averaged for the hour, and (2) read from the A-scope twice-hourly and averaged for the hour. The methods and results of these two comparisons are described.

COMPARISONS AT RADAR ECHO PERIPHERY

Stationary or slowly fluctuating circular sheet echo radar patterns are typical with an approaching offshore occluding frontal system and Low. They provide a means of comparing radar visibility because of the relative constancy of their outside edges. Hourly precipitation rates near the edge of such patterns are referred to in this paper as *threshold intensities*. The radar "detects" rain out to this edge but not beyond because of range attenuation and overshooting of the lower layers resulting from the earth's curvature. Figure 4 shows the average position of the weak echo periphery during a 13-hr. period on October 12, 1962, and a plot of average hourly station rainfall. Threshold intensity near this periphery is higher on windward slopes than on lee slopes.

An illustration of the increase in threshold intensity from coast to nearby slopes is shown in figure 2. Hourly estimated radar threshold intensity at the mountain station Boulder Creek and at nearby Sunset Beach on Monterey Bay are compared on January 30-31, 1963, when two

frontal systems passed inland (inset surface maps). The plotted data are hourly rainfall intensities during hours when each station was less than 5 mi. within or beyond the radar echo periphery. The much higher general level of the radar threshold intensity at Boulder Creek than at Sunset Beach, 8 mi. more distant from the radar, largely represents a lower reflectivity factor [6] in the predominantly orographic rain at Boulder Creek than in the convergence rain at Sunset Beach.

There is evidence from the same storm that threshold intensities in lee areas are low relative to the windward side. With no evident decrease in radar intensity at lee San Jose (fig. 1) relative to windward slopes, its threshold can be assumed lower with rainfall intensity one-fourth that at Boulder Creek.

Time variation in threshold intensity at a mountain location is believed to represent mainly variation in percentage of total precipitation due to orography. Thus while at an offshore gaging station threshold intensity varies little, threshold intensity at coastal mountain stations increases as convergence precipitation becomes light (judged by low intensity at nearby flat areas).

COMPARISONS AT RAIN GAGE SITES

Comparisons of radar rates of precipitation are made with gage rates. The underestimate of windward slope precipitation is suggested to result from orographic effects related to upslope wind.

Method.—By manual attenuation of the return signal intensity to zero, one can measure the reflectivity factor [6] for the echo on the A-scope at a particular azimuth and range and convert to rain intensity by the standard WSR-57 Rainfall Rate-Echo Intensity Chart [1]. At Sacramento twice-hourly estimates of rain intensity by this method were recorded by the radar meteorologist for selected Sierra foothill and upslope stations. Data used here are from storms during the period from December 1962, when radar performance was standardized [7], through January 1963.

A simple index of orographic precipitation on a slope is the upslope component of the 850-mb. wind. An estimate of this component from the Oakland 850-mb. wind is compared in figure 3 with the ratio of daily gage catch/twice-hourly radar-estimated daily rain during December 1962 and January 1963 storms.

Results.—Figure 3 suggests that precipitation at the two mountain stations, Brush Creek and Mt. Danaheer (inset), is poorly seen by radar (high ratio) on days with high wind components compared to days with lighter winds. A corresponding smaller trend in radar visibility at the foothill stations Beale Air Force Base and Oroville, where orographic precipitation is relatively small, indicates presence of other causal factors in the relations shown. These data suggest that the magnitude of the orographic component of rain on windward slopes is directly related to the percentage of gage catch underestimated by radar.

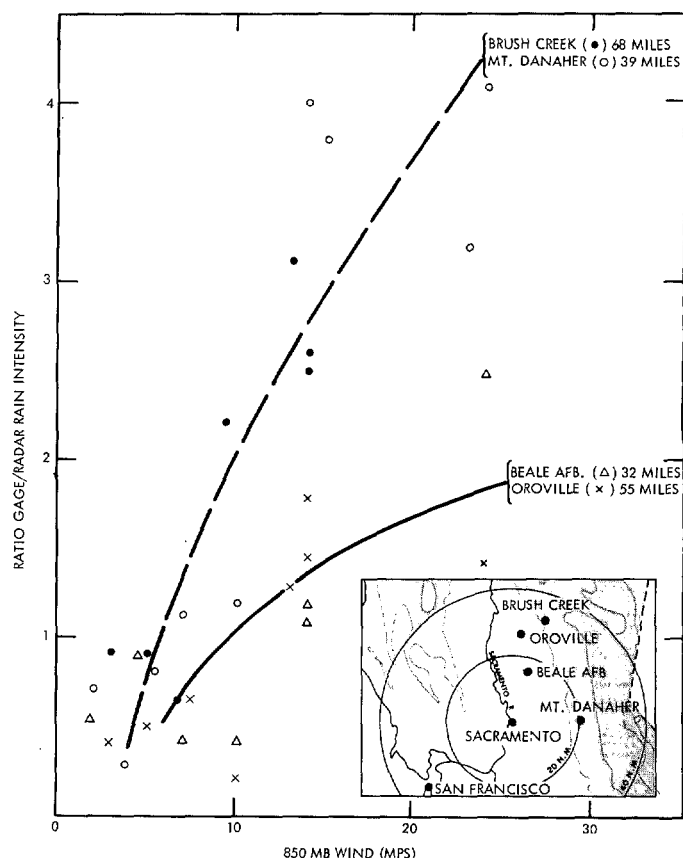


FIGURE 3.—Relation between 850-mb. wind component up Sierra slopes and the ratio of daily rain/average daily radar rate in December 1962 and January 1963 storms. Winds are based on Oakland data.

3. WEATHER PATTERNS AS SEEN BY RADAR

A simple grouping of radar echo patterns is: Stationary patterns (stationary fronts or widespread general convergence precipitation), moving frontal patterns, pre- and post-frontal patterns, and random cells. Examples of each are described in relation to the concurrent gage precipitation.

STATIONARY ECHO PATTERNS

Persistence of a sheet echo may portend important cumulative amounts. Such patterns permit intensity comparisons between the radar and gages. Two examples are given.

Deepening Low October 12, 1962.—To illustrate a typical radar pattern when a deepening Low approaches the coast the nearly stationary perimeters of the weak (equivalent to 0 to 0.2 in./hr.) and moderate (equivalent to 0.2 to 1.0 in./hr.) hourly radar echo areas were averaged during the period 0000–1300 PST October 12, 1962, shown by the dashed lines in figure 4. The Low and occluding wave are shown in the inset surface maps. A large orographic component places the corresponding gage rain centers on coastal and Sierra slopes. The area within the moderate

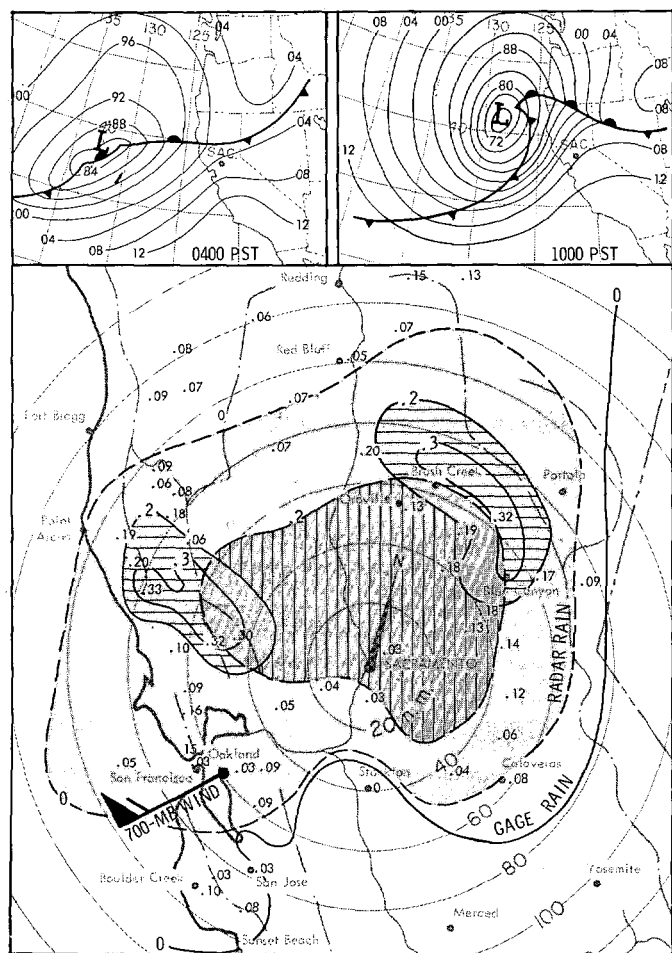


FIGURE 4.—Stationary echo pattern October 12, 1962. Average hourly radar (dashed lines) and gage (solid lines) rain intensities 0000–1300 PST are indicated during rapid deepening of the frontal system shown on insets. Intensities $> .2$ in./hr. are underestimated by radar in Sierras and coastal mountains (horizontal crosshatch). Intensities $< .2$ in./hr. are overestimated in the valley and foothills near the radar (vertical crosshatch). Numbers are average hourly gage rates in inches.

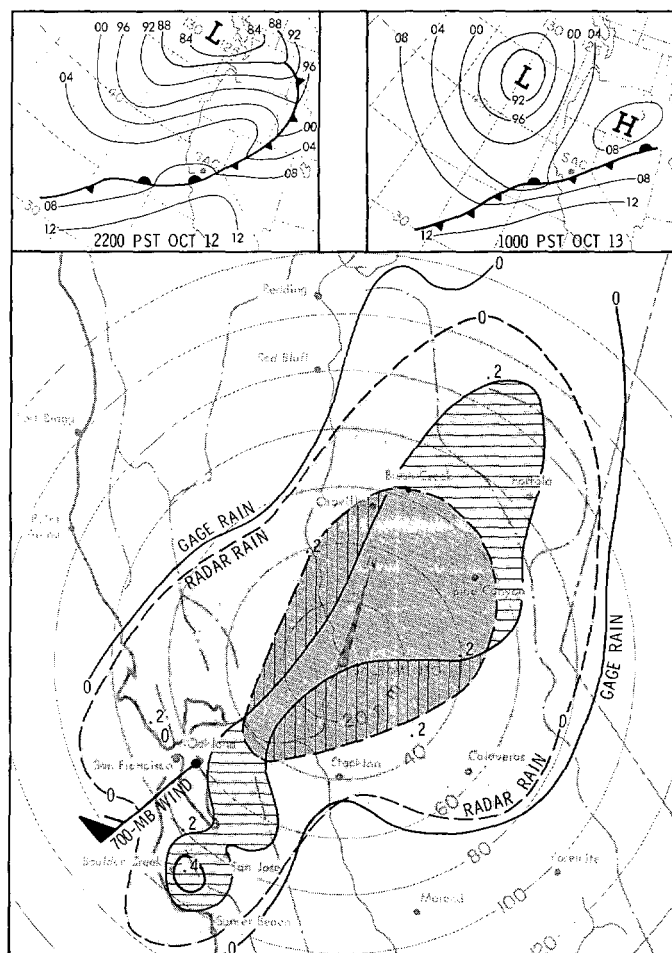


FIGURE 5.—Front stationary near radar 2200 PST October 12 to 1400 PST October 13, 1962. Average echo intensity (dashed lines) is compared with average hourly isohyets (solid lines). Horizontal crosshatch shows underestimate by radar in mountains to NNE and SSW with $> .2$ in./hr. actual intensity. Vertical crosshatch shows overestimate in close range areas observing $< .2$ in./hr. Moderate to strong cells moved at 40 kt. along front after 0700 PST, parallel to 700-mb. wind.

intensity radar periphery (0.2 in./hr.) is compared with those within the average 0.2 in./hr. isohyets as to location. The radar underestimates these gage rain centers with their large orographic component and of course overshoots the general light rain farther north. Within the moderate echo periphery it overestimates valley and foothill amounts, especially at close range.

Stationary Front October 12–13, 1962.—Another illustration of a stationary radar pattern is one encompassing a stationary front. Continuous rain from 2200 PST October 12 to 1400 PST October 13 resulted in extreme accumulations along a line NNE–SSW through Sacramento.

In figure 5 are shown isohyets of average hourly rain and average weak and moderate radar echo peripheries during this period in the same manner as in figure 4. The zero lines agree very well. The underestimate of the “moderate” rain by the radar on distant mountain slopes and the overestimate nearby is less marked than in the

previous illustration. This is because convergent rain is a larger portion of the total in mountain areas than in figure 4, borne out by comparison of valley and mountain gage amounts.

MOVING FRONTAL PATTERNS

Radar detection of most northern California frontal systems involving appreciable rain is hindered by precipitation associated with the accompanying Low or trough. Two examples are described. Far less frequent is a strong echo gradient across the front, evident even in mountain areas; such a front is described as a contrast to fronts obscured on radar.

Typical of frontal patterns obscured by general cyclonicity and orographic rain are occluding waves moving northeastward around deep offshore Lows, and, in contrast, a southeastward-moving occluding system in a Low. Examples are given in that order.

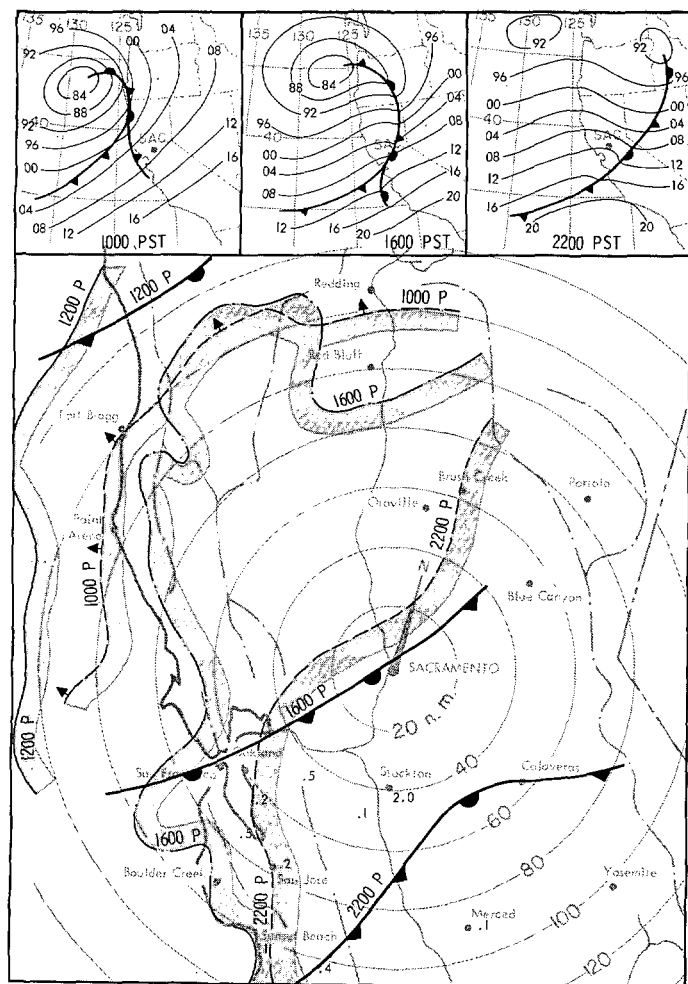
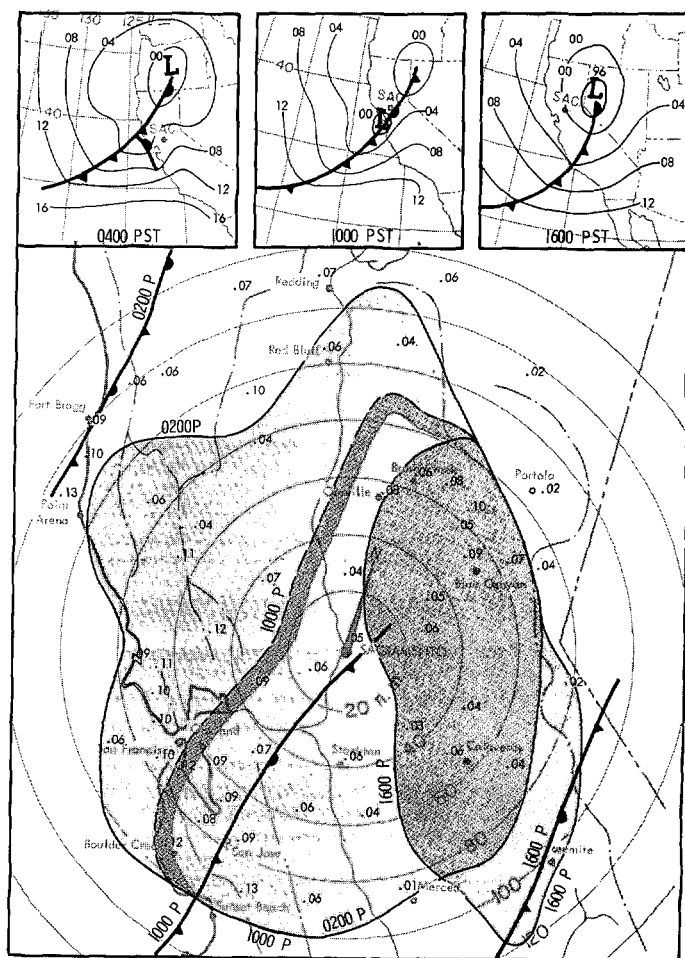


FIGURE 6.—Movement of echo periphery and occlusion January 31, 1963. Periphery expands toward front from 1000 to 1200 PST then lags behind front, especially at 1600 PST. Surface maps are shown as insets. Frontal rain (in.) varies widely south of Sacramento as a result of irregular movement of front.

Obscured frontal pattern January 31, 1963.—This front, as it moved out of a deep offshore trough, was obscured in a broad field of convergence precipitation and heavy orographic precipitation on southwest-facing slopes. Frontal positions are shown in figure 6 (and on inset surface maps), along with echo peripheries. Overshooting to northwest limited radar range to 120 mi. at 1000 PST (fig. 6). But by 1200 PST the weak echo periphery reached out to 160 mi. at the front, and small moderate echo areas (not shown), first appearing at 0900 PST over lee slopes near the radar, were shifting southeastward. The back edge of the echo pattern followed the front but trailed by a considerable distance over coastal mountains during the afternoon and later over the northern Sierras as orographic rain continued behind the front. An irregularity on the front in the northern San Joaquin Valley, at 2200 PST, apparently was related to channeled cross-isobaric low-level flow. It caused wide variation in rain, 0.1 in. at Merced and 2.0 in. at Stockton.



of this storm. Direction of approach of the Low was from northwest instead of southwest; precipitation was mostly snow in mountains instead of rain; and freezing level was at 1,500–2,500 ft. compared to 13,000 ft. Echo tops near the front were generally less, and radar range was considerably less, around 100 mi.

The frontal positions on radar (fig. 7) were obscured by widespread convergence precipitation associated with the Low. General expansion of echo periphery in all directions took place from 2200 PST to the position shown at 0200 PST as the front moved into northwestern California and a weak Low center formed on the front along the coast by 0400 PST (fig. 7 inset).

Weak surface winds or directions nearly parallel to slopes kept the orographic component of hourly amounts small. Station average hourly precipitation (fig. 7) was little higher in mountains than upwind. A few normally lee areas received more precipitation than some normally windward stations nearby. Only near the end of the storm is an orographic effect evident, over the central Sierra slopes in the 1600 PST pattern.

A distinct front.—Radar displays demonstrate that general precipitation obscures frontal precipitation outlines. Thus weak fronts are distinct on radar only when precipitation is confined to the front, while strong fronts, even when embedded in a general rain pattern, may appear distinctly if the rain stops temporarily immediately ahead of the front. On October 12, 1962, rain intensity at the front (fig. 8) was one of the highest yet measured on the Sacramento radar. Record winds over extreme northern California and Oregon accompanied the deep Low shown moving northward along the coast on the surface maps at 1000 PST and 1600 PST (fig. 8 insets). Frontal intensification at the coast is evident. The front was not detected by radar offshore to the west. It could barely be seen at 100 mi. (off Point Arena) at 1300 PST, just before 1.10 in. fell there in 20 min. But at 1500 PST it appears on figure 8 as a band of strong cells. During this time there was a brief cessation of general light rain just ahead of the front, apparent on precipitation traces and on the isohyetal and radar patterns (fig. 8). This is attributed to divergence in the strong southwest flow in response to the contiguous strong isallobaric field associated with the front.

Figure 9 compares 1-hr. rain amounts at 1800 PST with average radar-estimated intensity during that hour along a line through Sacramento normal to the front. Instantaneous radar rates were more extreme; rates of nearly 5 in./hr. were confirmed by lysimeter measurements at Davis, 13 mi. due west of Sacramento. Stalling and weakening of the front began after 1800 PST (fig. 5 inset); by 2200 PST only a broad moderate echo of uniform intensity remained.

Highest 20-min. rainfall amounts during frontal passage (fig. 8) were at Point Arena on the coast and at Red Bluff and Oroville in the Sierra foothills. Amounts averaged slightly higher than elsewhere at coastal mountain stations

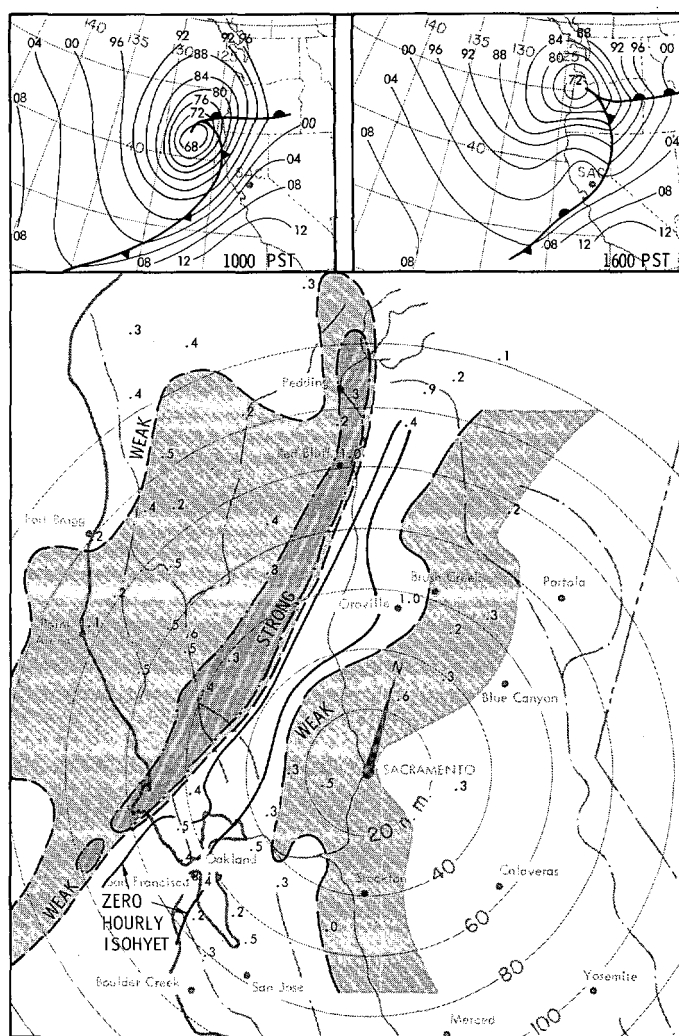


FIGURE 8.—Strong cold front 1500 PST October 12, 1962. An area of no rain separates preceding weak sheet echo (dashed lines) and strong-celled frontal echo (dash-dot lines). Highest 20-min. rain (in.) at the front favors foothill stations. Insets show surface maps.

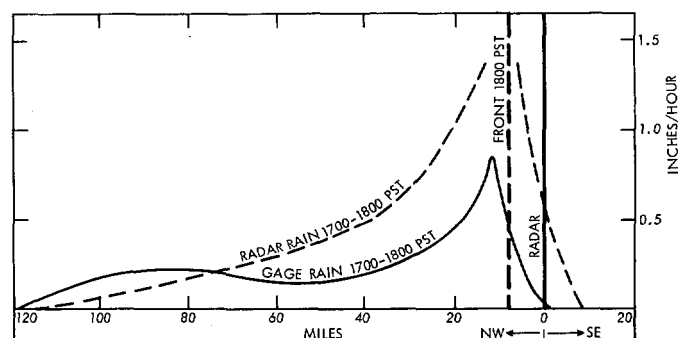


FIGURE 9.—Gage- and radar-measured hourly rain intensity along a line through Sacramento normal to the front at 1800 PST, October 12, 1962.

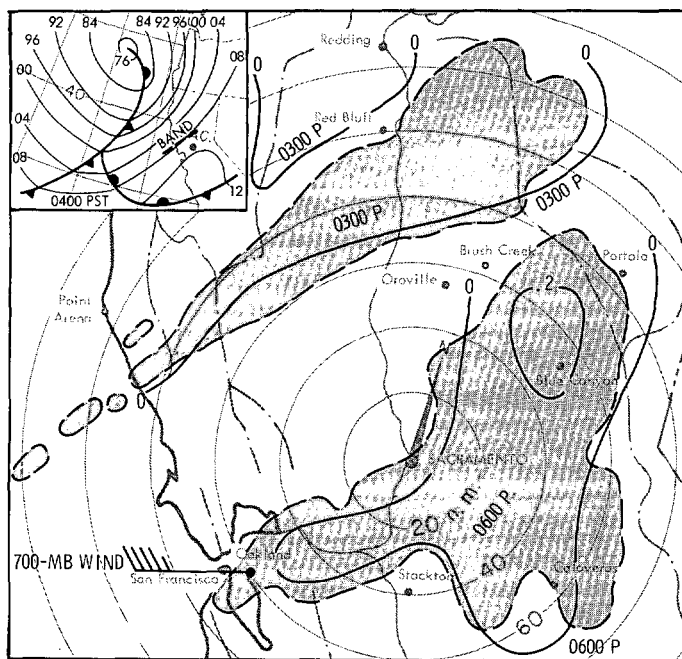


FIGURE 10.—Prefrontal weak echo pattern, October 11, 1962. Movement is normal to Oakland 700-mb. winds into low-level ridge. Hourly isohyets are solid lines, radar patterns dashed lines. Inset surface map shows band and fronts at 0400 PST.

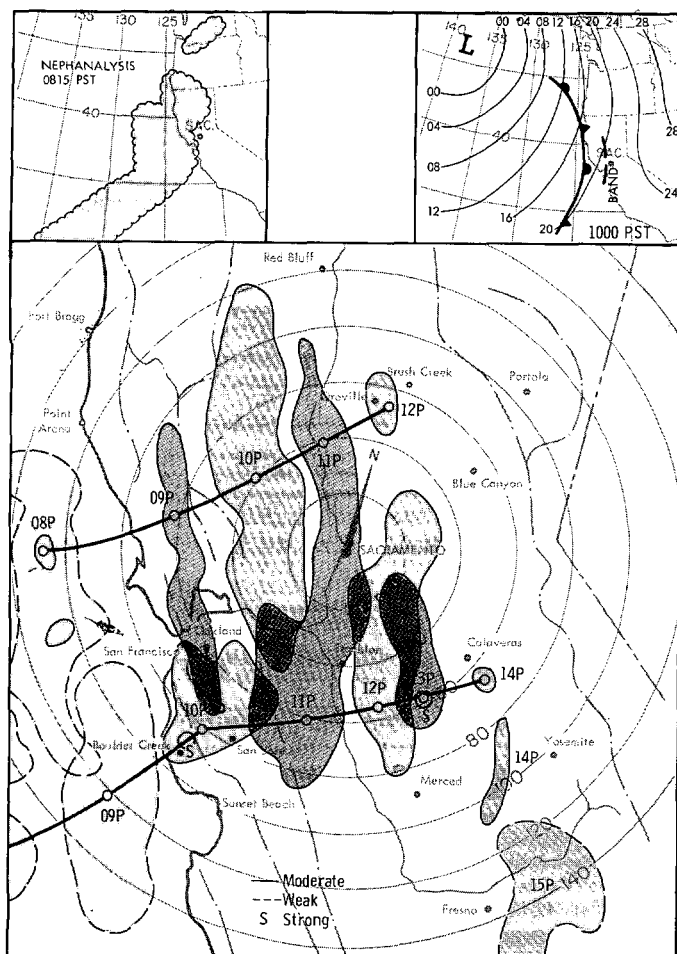


FIGURE 11.—Prefrontal radar band on February 12, 1963, one of five bands moving ahead of occlusion and fading over Sierras. Insets show 0815 PST TIROS nephanalysis and 1000 PST surface map.

having high mean seasonal values. In contrast, Sierra slope amounts decreased with elevation, presumably in response to decreasing moisture in the air column. A lee evaporation effect is evident in the slightly lower values east of the coastal mountains. This frontal rain pattern graphically illustrates that increase in foothill rain occurs when terrain stimulates release of instability.

PRE-FRONTAL BANDS

Radar substantiates movement of precipitation bands ahead of fronts, sometimes apparent in isochrone analysis of precipitation bursts. Orientation of band axis varies. Examples are given of motion with and normal to the wind.

October 11, 1962.—Moving out ahead of the offshore front shown at 0400 PST in figure 10 inset surface map, this weak radar band was well marked. Isohyets and radar patterns indicate a predominance of rain over Sierra slopes and evaporation of rain seen by radar over the Central Valley. The direction of movement of the band was normal to 700-mb. winds and toward higher surface pressure. Cell motion along the axis of the band was at the indicated 700-mb. wind speed. The band faded rapidly after 0600 PST.

February 12, 1963.—An unusual series of five precipitation bands, embedded in the forward part of the neph-analysis shown in the figure 11 inset, moved onshore in northern California on February 12, 1963, in advance of a weak occlusion. The third band of the series is shown in figure 11 and, in relation to the front, on the 1000 PST inset surface map. The band appears to increase in strength from weak offshore to moderate near the radar, in part the result of initial overshooting and later insufficient range correction. The band was segmented prior to 1100 PST. Hail and lightning were reported in the stronger cells prior to 1000 PST. The band faded rapidly over the Sierras by 1500 PST. The four other bands behaved similarly.

POST-FRONTAL STRATIFIED BAND

An example is shown in figure 12 of an organized rain band following a front which had moved out of a deep offshore trough late on October 13, 1962 (fig. 12 inset). For clarity, after 1800 PST only moderate peripheries of the band are shown at 2-hr. intervals. The radar indicated a short interval of time between the previous frontal rain and that of the post-frontal band. The band moved southeastward and faded out after 0000 PST. The radar intensity does not reflect windward increase and leeward decrease of rain amounts, evident in the totals of the band rain plotted in tenths of an inch.

RANDOM CELLS

Cells often continue to form at random after a frontal passage in an unstable flow from a continuing offshore trough. A typical example is shown in figure 13. Hourly peripheries of the cells that formed in a broad sheet echo during the night of January 30, 1963 are shown, moving with the 700-mb. wind direction. One cell is still visible

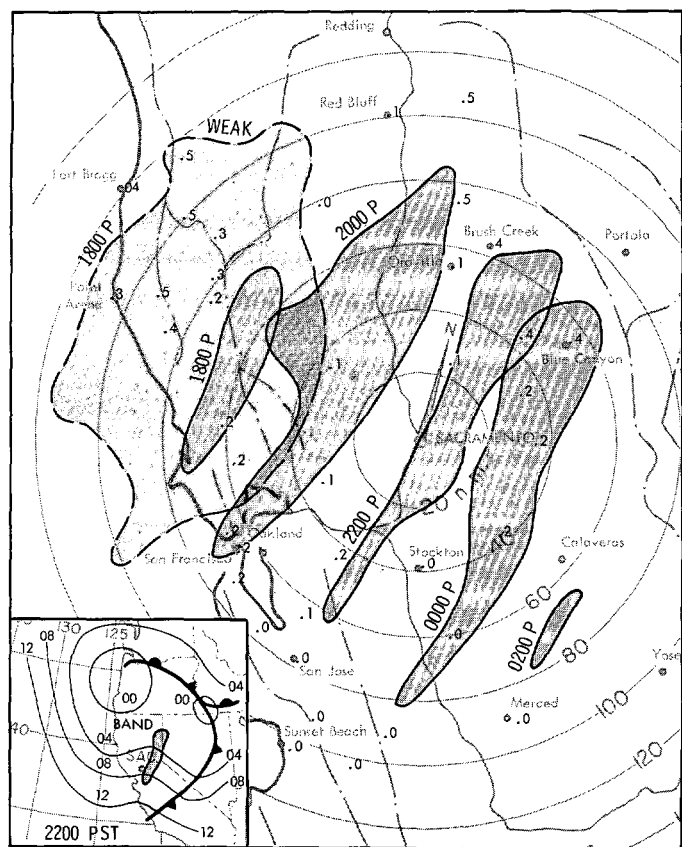


FIGURE 12.—Post-frontal moderate echo band 1800 PST October 13 to 0200 PST October 14, 1962. Movement and fadeout to southeast are shown in relation to front on inset surface map. Radar intensity overestimates band rain amounts (shown as tenths of an inch) in lee evaporation areas. Weak echo outline is shown only at 1800 PST.

beyond the Sierra crest. They were embedded in the shower area outlined on the 0100 PST surface map (fig. 13 inset) which was overtaken at 0400 PST by an approaching warm front sheet echo. Plotted in or near each cell outline in figure 13 under the hour (PST) is the estimate of average hourly gage intensity (hundredths) within the echo periphery. Amounts appear to decrease in the Central Valley.

4. CONCLUSIONS

Radar measurement of precipitation intensity is complicated in mountain areas by undersetimation of precipitation on windward slopes and overestimation on lee slopes. This is so because precipitation due to orographic lifting forms at low levels and is of smaller than average drop size, whereas in lee areas detected precipitation is depleted as it falls through dry lower levels of the air. Recognition of these effects allows better interpretation of the radar echo-intensity pattern in terms of precipitation amounts.

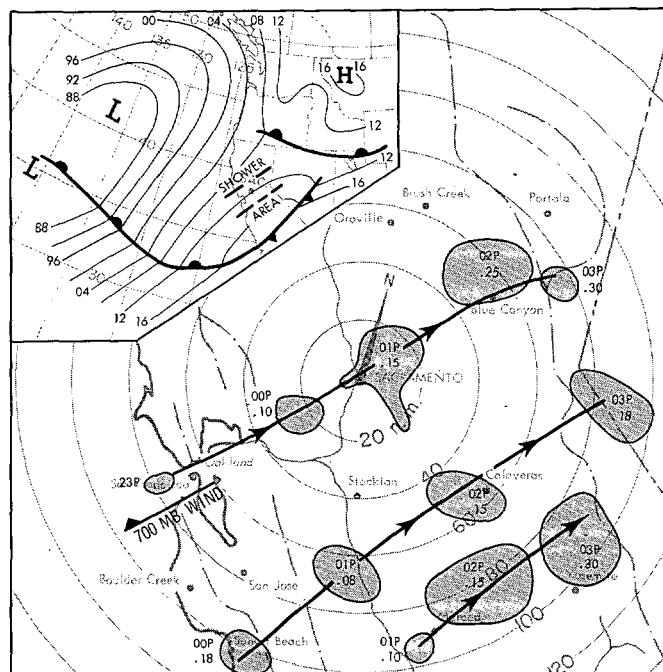


FIGURE 13.—Post-frontal random cells on the night of January 30, 1963. Figures are time/average hourly intensity (in.) within the echo. Inset 0100 PST surface map shows shower area in relation to fronts.

The radar patterns aid in positioning weather systems. A distinct frontal pattern may have an irregular shape with weak and strong segments or a temporary dual structure. Such irregularities are sometimes evident in gage rainfall. Terrain may cause much of this disturbance of the simple structure. But most fronts are located only approximately by the radar, and then only after there is evidence of clearing on the back side. While even this evidence may be lacking over windward mountain slopes when strong upslope winds and orographic precipitation persist, post-frontal orographic precipitation is poorly observed by radar except at close range. Organized convergence bands appear on radar that are not explainable on surface maps or associated with fronts. They may cause more precipitation than the fronts and if not identified by radar may confuse placement of fronts.

ACKNOWLEDGMENTS

The success of this study depended on the cooperation of the staff of the Sacramento Weather Bureau Office and the radar information documented by the radar meteorologists.

REFERENCES

1. U.S. Weather Bureau, *Weather Surveillance Radar Manual*, Washington, D.C., Chapt. 3, p. 43.
2. J. W. Wilson, "Evaluation of Precipitation Measurements with the WSR-57 Weather Radar," *Journal of Applied Meteorology*, vol. 3, No. 2, Apr. 1964, p. 165.

3. D. Atlas, "Advances in Radar Meteorology," *Advances in Geophysics*, vol. 10, Academic Press, New York, 1964, pp. 317-478.
4. D. M. A. Jones and E. A. Mueller, "Z-R Relationships from Drop-Size Data," *Proceedings of 8th Weather Radar Conference*, San Francisco, Apr. 1960, pp. 498-504.
5. V. A. Myers and G. A. Lott, "Three-Dimensional Wind Flow and Resulting Precipitation in a Northern California Storm," *Research Paper No. 44*, U.S. Weather Bureau, Washington, D.C., 1963, 46 pp. (see fig. 47).
6. L. J. Battan, *Radar Meteorology*, University of Chicago Press, Chicago, 1959, 161 pp. (p. 30).
7. S. G. Bigler and M. W. Brooks, "Standardization of Performance of WSR-57 Radars," *Proceedings of the 10th Weather Radar Conference*, Washington, D.C., Apr. 1963, pp. 330-334.

[Received March 22, 1966; revised May 4, 1966]